

# **Incorporation of UV Radiances Into the USU GAIM Models**

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## **LONG-TERM GOALS**

Our primary goal is to incorporate UV radiances from the SSULI and SSUSI instruments, which will be flown on the NPOSSE satellites, into the USU GAIM models. A secondary goal is to conduct GAIM simulations in order to elucidate the physics underlying equatorial spread F and plasma bubbles.

## **OBJECTIVES**

The primary USU data assimilation model is the Full Physics Kalman Filter (FPKF) model. It provides specifications and forecasts on a spatial grid that can be global, regional, or local. It uses a physics-based ionosphere-plasmasphere-polar wind model and a Kalman filter as a basis for assimilating a diverse set of real-time (or archived) measurements, and it is capable of assimilating in situ and remote sensing satellite data as well as ground-based data. The resulting specifications and forecasts are in the form of 3-dimensional electron density distributions from 90 km to 30,000 km. In addition, the FPKF model can provide global distributions for the self-consistent ionospheric drivers (neutral winds, electric fields, and particle precipitation patterns), and in its specification mode, it provides quantitative estimates for the accuracy of the reconstructed plasma densities. Because of the usefulness of this data assimilation model for DoD applications, we proposed to add an additional data source in the assimilation scheme and then conduct relevant scientific studies. Specifically, we proposed to accomplish the following objectives: (1) Assimilate UV radiances into our FPKF model and then conduct an extensive validation of the procedure; (2) Develop algorithms to assimilate data from a UV imager in a geostationary orbit; (3) Study the effect of the plasmasphere on slant Total Electron Content (TEC) measurements obtained from GPS ground receivers; and (4) Conduct simulations in an effort to determine the background ionospheric conditions just prior to the onset of equatorial spread F.

## **APPROACH**

The Full Physics Kalman Filter model was developed at USU as part of a DoD Multidisciplinary University Research Initiative (MURI) program. The USU effort was called Global Assimilation of Ionospheric Measurements (GAIM), and the Full Physics data assimilation model was one of the two GAIM models developed. This model rigorously evolves the ionospheric (and plasmaspheric) electron density field and its associated errors using the full physical model. Advantages of this rigorous approach are expected to be most significant in data-sparse regions and during times of “severe weather.” Necessary approximations to make the model computationally tractable capitalize on the

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newest developments in oceanographic data assimilation (Daley, 1991). The model is based on a new physics-based model that is composed of an Ionosphere-Plasmasphere Model (IPM) that covers low and mid-latitudes and an Ionosphere-Polar Wind Model (IPWM) that covers high latitudes. These new physics-based models are state-of-the-art and include six ion species ( $\text{NO}^+$ ,  $\text{O}_2^+$ ,  $\text{N}_2^+$ ,  $\text{O}^+$ ,  $\text{He}^+$ ,  $\text{H}^+$ ), ion and electron temperatures, and plasma drifts parallel and perpendicular to the geomagnetic field. These models use the International Geomagnetic Reference Field, which accurately describes the relative positions of the geographic and geomagnetic equators and the declination of the magnetic field lines. The physics-based models cover the altitude range from 90 to 30,000 km, which includes the E-region, F-region, topside ionosphere, plasmasphere, and polar wind. The different real-time data sources are assimilated via a Kalman filter technique and quality control algorithms are provided as an integral part of the full Kalman filter model (Schunk *et al.*, 2004; Scherliess *et al.*, 2004).

The other data assimilation model developed as part of GAIM is the Gauss-Markov Kalman Filter (GMKF) model. This data assimilation model is based on the Ionosphere Forecast Model (IFM; Schunk *et al.*, 1997), which covers the E-region, F-region, and topside ionosphere up to 1400 km, and takes account of six ion species ( $\text{NO}^+$ ,  $\text{O}_2^+$ ,  $\text{N}_2^+$ ,  $\text{O}^+$ ,  $\text{He}^+$ ,  $\text{H}^+$ ). However, the output of the model is a 3-dimensional electron density distribution at user specified times. In addition, auxiliary parameters are also provided, including  $N_mF_2$ ,  $h_mF_2$ ,  $N_mE$ ,  $h_mE$ , slant and vertical TEC. In the Gauss-Markov Kalman Filter, the ionospheric densities obtained from the IFM constitute the background ionospheric density field on which perturbations are superimposed based on the available data and their errors. To reduce the computational requirements, these perturbations and the associated errors evolve over time with a statistical model (Gauss-Markov process) and not, as in the case of a Full-Physics-Based Model, rigorously with the physical model. As a result, the Gauss-Markov Kalman filter can be executed on a single CPU workstation. Like all assimilation techniques, the Gauss-Markov Kalman filter uses the errors on the observations and model in the analysis, and computes the errors in the match. The Gauss-Markov Kalman filter model is a global model that can support regional, higher definition assimilation windows within the model specification.

## WORK COMPLETED

The primary goal of the project was to incorporate UV radiances from the SSULI and SSUSI instruments into the USU GAIM models. A secondary goal was to conduct science studies related to elucidating the fundamental processes that operate in the ionosphere, including the low-, mid-, and high-latitude domains. During the three-year project, we accomplished the following:

- (1) We acquired 1356 Å emission data for the SSULI-type instrument and developed an algorithm to incorporate the data into our Gauss-Markov Kalman Filter model. We also assisted in defining the SSUSI SDR format specification to meet the GAIM requirement, and then we acquired 1356 Å UV radiances from the SSUSI instrument onboard the DMSP F16 satellite. We acquired 40 days (days 84-122, 2004) of limb radiances from Paul Straus. Subsequently, we performed a preliminary test run of the Gauss-Markov Kalman filter using the SSUSI UV radiances, and during the third year we conducted an additional series of tests;
- (2) The Gauss-Markov Kalman filter model was upgraded to include the following important additional features: (a) a hot start capability; (b) the use of latent data (up to 3 hours); (c) an updated Ionosphere Forecast Model (IFM); and (d) an updated GPS-TEC data reduction

algorithm. This improved Gauss-Markov model was delivered to NRL and AFWA on 15 January 2005 as operational Version 2.2;

- (3) The Air Force Research Laboratory (AFRL) conducted an extensive validation of our Gauss-Markov model by comparing model output to independent ionosonde data and by examining 640,000 altitude profiles. Occasionally, some of the electron density profile shapes were not quite correct. We tracked down the funny profiles and corrected the problems. We also improved the use of our GPS-TEC error estimates. This updated Gauss-Markov model was delivered to NRL and AFWA on 15 July 2005 as operational Version 2.3;
- (4) We expanded our GAIM simulations for the low-latitude ionosphere to include additional longitudinal sectors and a paper was submitted for publication with NRL colleagues (McDonald et al.; Extreme Longitudinal Variability of Plasma Structuring in the Equatorial Ionosphere on a Magnetically Quiet Equinoctial Day);
- (5) We began a comprehensive validation of the  $N_e$  densities obtained from the Ionosphere Forecast Model (IFM) at 840 km at high latitudes by comparing them to in situ DMSP satellite measurements. Typically, the IFM  $N_e$  densities at 840 km in the polar cap were lower than the measurements by about a factor of 2, indicating that either the density scale height above the F-region peak was too small (e.g., the plasma temperature was too small) or the neutral atomic oxygen density was too small. The study was completed and a paper was submitted for publication (Bekerat et al., 2006). The main parameter responsible for the factor of two discrepancy was the downward electron heat flux at the IFM's upper boundary (1400 km), and a one-time adjustment of this parameter was needed to bring the IFM  $N_e$  into agreement with the DMSP  $N_e$  in the polar cap;
- (6) We submitted a paper for publication entitled "Duration of an ionospheric data assimilation initialization of a coupled thermosphere-ionosphere model" by Jee et al. (2006).
- (7) A publication that provides a comprehensive description of our Gauss-Markov data assimilation model has been accepted for publication. The paper by Scherliess et al. (2006) is entitled "The USU GAIM Gauss-Markov Kalman filter model of the ionosphere: Model description and validation" and it is briefly described below.
- (8) Several GAIM papers and talks were presented at scientific meetings, including the Fall and Spring AGU Meetings, the CEDAR meeting, Space Weather Week, the Ionospheric Effects Symposium, the URSI Meeting, and the IAGA Meeting in Toulouse, France.

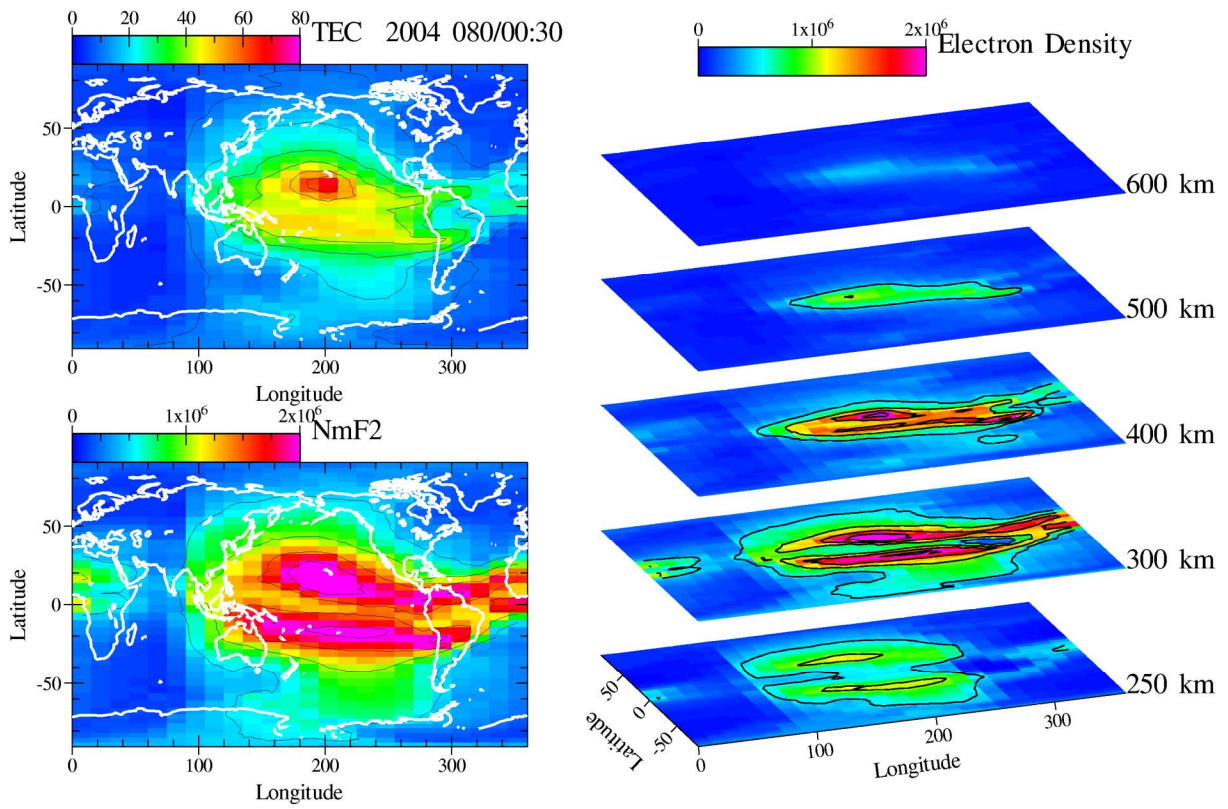
## RESULTS

In an operational setting, the Gauss-Markov Kalman Filter model runs continuously and reconstructs the global electron density distribution as a function of time. The model automatically acquires the relevant data on the web, quality controls the data, inputs the data into the Kalman filter, and outputs a variety of ionospheric parameters at a 15- minute cadence. The data assimilated can include slant TEC from up to 1000 ground GPS receivers, bottom-side electron density profiles from 20 digisondes, in situ electron densities from several DMSP satellites, and integrated UV emissions from satellites. In practice, however, different amounts of data are assimilated, depending on the data availability. In

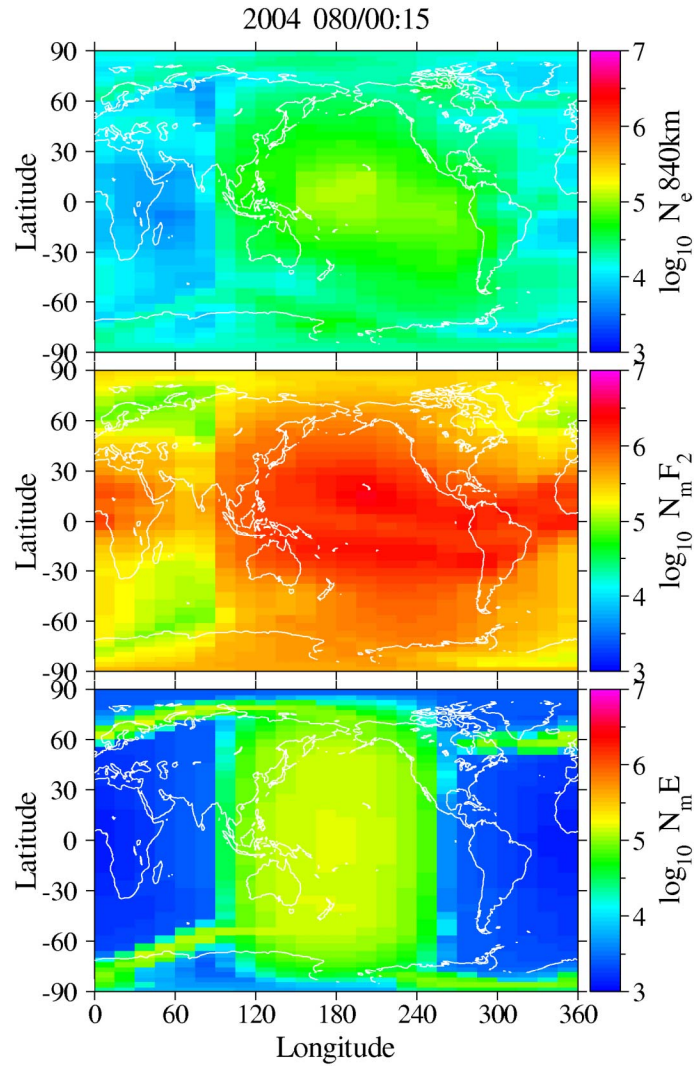
general, occultation data can also be assimilated, but that capability is not included in the version that was delivered for operational use.

Figures 1-3 are from a recent paper by *Schunk et al.* (2005) and they show some of the standard output parameters of the Gauss-Markov model from an example 1-month ‘equinox period’ that was delivered with the operational model (days 80 - 110 in 2004). For this period, the assimilated data included slant TEC from 162 GPS ground receivers, bottom-side  $N_e$  profiles from 17 digisondes, and in situ  $N_e$  from DMSP satellites F13, F14, and F15. Figure 1 shows snapshots (at 00:30 UT on day 80) of vertical TEC obtained by integrating through the  $N_e$  distribution from 90-1400 km (top-left panel),  $N_m F_2$  (bottom-left panel), and contours of  $N_e$  at selected altitudes (right panel). Clearly evident in both  $N_m F_2$  and TEC are the equatorial anomaly peaks. Figure 2 shows snapshots (at 00:15 UT on day 80) of  $N_m E$ ,  $N_m F_2$ , and  $N_e$  at 840 km. Output of these parameters is routinely tracked to make sure that the E-region, F-region, and topside behave properly after the various data types are assimilated. Finally, Figure 3 shows snapshots of  $N_e$  profiles at selected locations (high, middle and low latitudes) along longitudes relevant to the North American and European/African sectors. Note that at high latitudes the peak in  $N_e$  can occur in the E-region due to auroral particle precipitation.

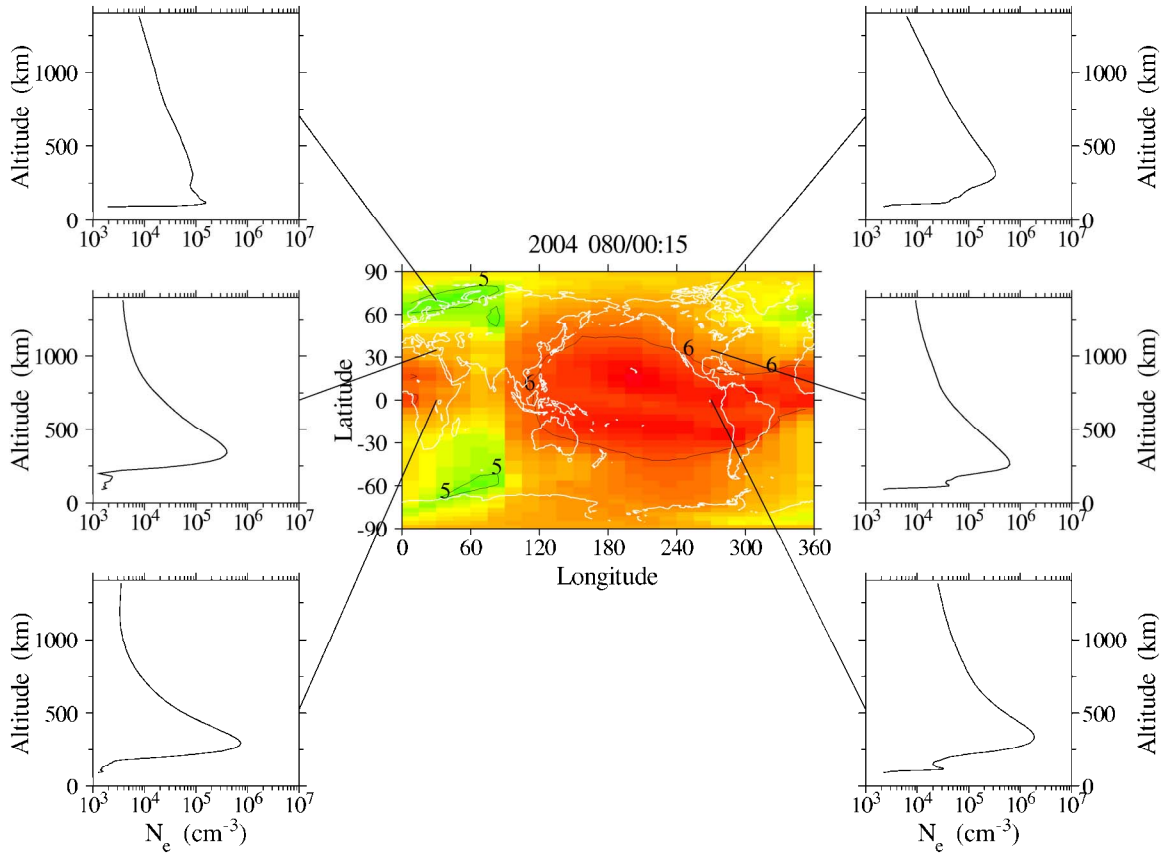
The Gauss-Markov model was designed to be flexible and, as noted earlier, it can also be applied to just one region. Figure 4 shows a sample of the output for a regional simulation. For this case, a three-dimensional ionospheric reconstruction across North America was considered and the simulated period was November 20-21, 2003, which was when a large geomagnetic storm occurred. The data included TEC measurements from more than 300 GPS receivers and bottom-side electron density profiles from ionosondes at the Dyess (Texas) and Eglin (Florida) stations. During the reconstruction, about 2000 slant TEC values were assimilated every 15 minutes. The bottom panel in Figure 4 shows the data (slant TEC converted to the vertical with an angle factor) at a given instant of time. The top panel shows the vertical TEC obtained from the physics-based Ionospheric Forecast Model (no data assimilation), and the middle panel shows the Gauss-Markov Kalman Filter TEC obtained from the ionospheric reconstruction when the data are assimilated into the physics-based model. Clearly, the data make a significant contribution to the reconstruction.



**Figure 1. Sample output from the operational Gauss-Markov Kalman filter model. Shown in the figure are vertical TEC (upper-left panel),  $N_mF_2$  (lower-left panel), and contours of  $N_e$  at selected altitudes (right panel). The results are for day 80, 2004, at 00:30 UT, and they are displayed in a geographic latitude-longitude coordinate system.**

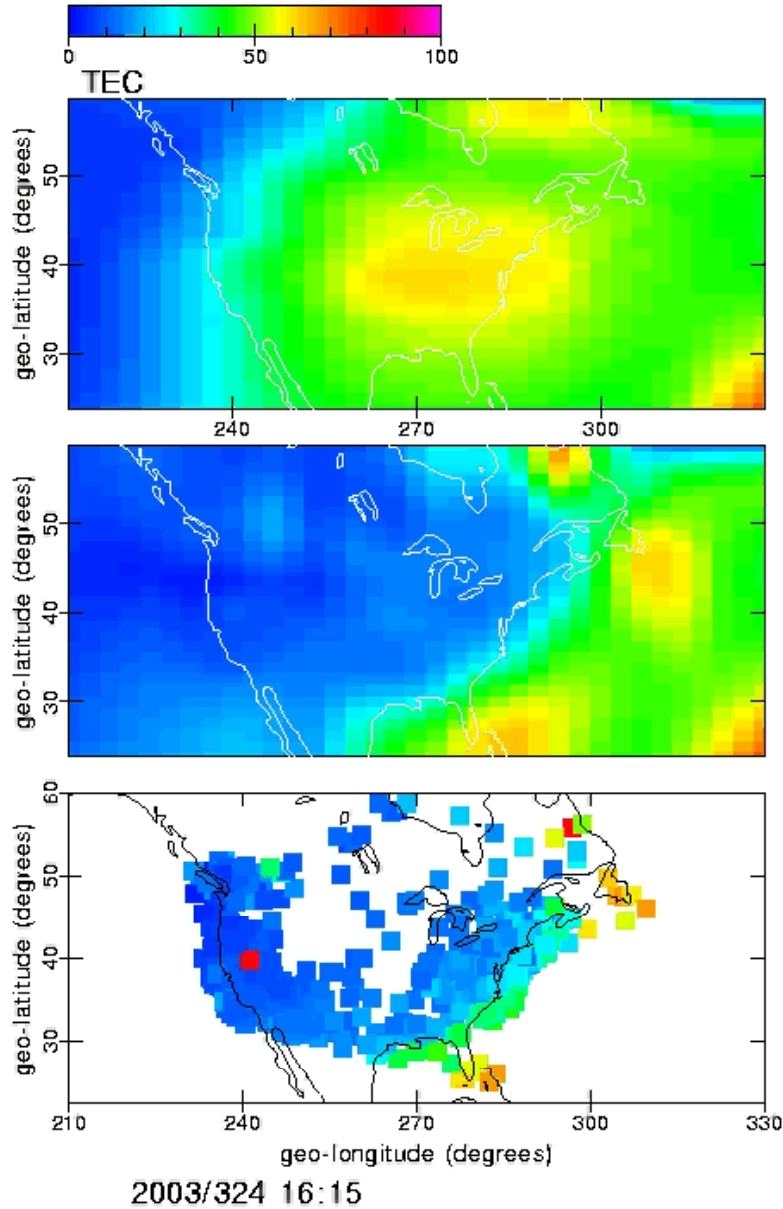


**Figure 2.** Snapshots of  $N_m E$  (bottom),  $N_m F_2$  (middle), and  $N_e$  at 840 km (top) for day 80, 2004, at 00:15 UT. The parameters are displayed in a geographic coordinate system.



**Figure 3.** *Altitude profiles of  $N_e$  at high, middle, and low latitudes for longitudes that pass through North America and Africa. The profiles are for day 80, 2004, at 00:15 UT. The middle panel shows  $N_m F_2$ .*





**Figure 4. Sample output from a regional ionospheric reconstruction using the Gauss-Markov Kalman Filter model. The output corresponds to 16:15 UT on day 324, 2003.**

As a part of the validation effort for the USU GAIM project, an improved Ionosphere Forecast Model (IFM) was validated using a large database of TOPEX TEC measurements (Zhu *et al.*, 2005). The TOPEX data used for the validation was for the period from August 1992 to March 2003 and the total number of 18-second averaged data was close to 11 million. This model validation work covered a wide range of seasonal (winter, summer, equinox) and solar (low, median, and high F10.7) conditions as well as all UT variations. The validation results indicated that the features of the spatial distribution of the IFM TEC are systematically consistent with those of the TOPEX TEC. The differences between the IFM TEC and the TOPEX TEC are within 20% for almost all locations and conditions. For many conditions, the differences are even less than 10%.

In a scientific study, we investigated the extreme longitudinal variability of equatorial scintillation under quiet magnetic conditions during March 22-23, 2002 (*McDonald et al., 2005*). SCINDA exhibited intense activity in the South American-Atlantic sector during local evening hours, whereas an absence of scintillation was seen in the Far-East Asian sector. Ground and space-based measurements from SCINDA, GUVI, TOPEX and a chain of GPS receivers were used in combination with a data assimilation model to explore the relationship between the large-scale ionization distribution and small-scale irregularities at low latitudes in the scintillating and non-scintillating longitude sectors. Global GPS TEC measurements were assimilated into the USU-GAIM model to provide a global model of electron density profiles for March 22-23. The TOPEX and GUVI TECs compared well with the USU-GAIM results in the Far-East Asian sector; however, the model could not be used to specify the background ionosphere after the onset of scintillation in the South American-Atlantic sector. TECs derived from the South American chain of GPS receivers were used to investigate the large-scale ionization distribution in the scintillating sector. A comparison of the USU-GAIM TECs in each sector showed that there are significant differences in the evolution of the ionization distributions during the evening hours, likely the result of differences in the daytime and post-sunset vertical plasma drift in the two sectors. This study demonstrates the importance of USU-GAIM as a new tool for investigating longitudinal as well as day-to-day variability that is observed in the large-scale distribution of the ionosphere and how this relates to the occurrence of scintillation.

In the paper by Scherliess et al. (2006), we described our Gauss-Markov Kalman Filter (GMKF) model. The GMKF uses a physics-based model of the ionosphere and a Gauss-Markov Kalman filter as a basis for assimilating a diverse set of real-time (or near real-time) observations. The physics-based model is the Ionospheric Forecast Model (IFM), which accounts for five ion species and covers the E-region, F-region and the topside from 90 to 1400 km altitude. Within the GMKF, the IFM derived ionospheric densities constitute a background density field on which perturbations are superimposed based on the available data and their errors. In the current configuration, the GMKF assimilates slant total electron content (TEC) from a variable number of global positioning satellite (GPS) ground sites, bottom-side electron density ( $N_e$ ) profiles from a variable number of ionosondes, in situ  $N_e$  from four Defense Meteorological Satellite Program (DMSP) satellites, and nighttime line-of-sight ultraviolet (UV) radiances measured by satellites. To test the GMKF for real-time operations and to validate its ionospheric density specifications, we have tested the model performance for a variety of geophysical conditions. During these model runs various combination of data types and data quantities were assimilated. To simulate real-time operations, the model ran continuously and automatically, and produced 3-dimensional global electron density distributions in 15-minute increments. In this paper, the Gauss-Markov Kalman filter model and the results of our validation study with independent observations are presented.

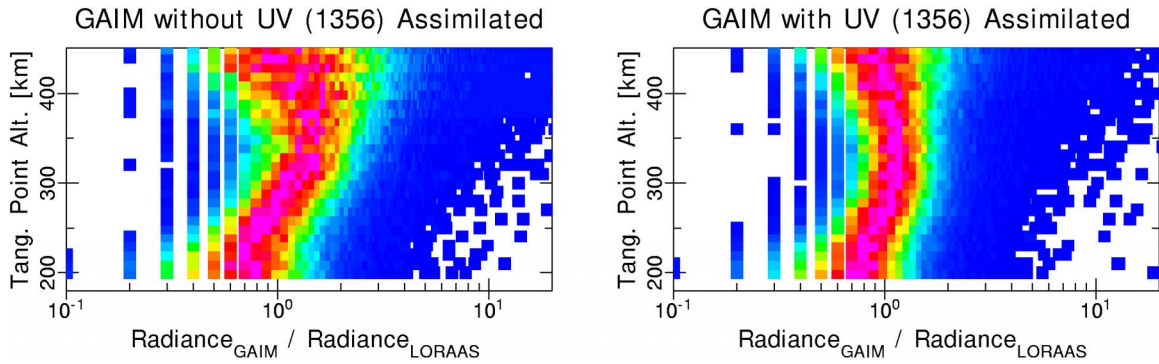
#### *Validation Studies:*

We have performed several validation studies of our Gauss Markov Kalman filter model and these are summarized here for completeness.

To better guide the assimilation of the nighttime UV limb scan radiances, Scherliess et al. [2005] compared 911 and 1356 Å nighttime radiances obtained from the USU GAIM data assimilation model with limb scan observations from the LORAAS and the SSULI instruments. This comparison was performed for different geophysical conditions. For this study, the GAIM model assimilated slant TEC

from a variable number of ground GPS sites, bottomside  $N_e$  profiles from a variable number of ionosondes, and in situ  $N_e$  from DMSP satellites and provided the 3-D global plasma density distribution in 15-min increments. The ionospheric plasma densities obtained from our GAIM model were then used to calculate associated UV radiances, which were directly compared with the observations. It was found that the 1356 Å LORASS and the 911 Å SSULI radiances agree well with the USU GAIM model results. However, the 1356 Å radiances obtained from the SSULI instrument were found to be different by a factor of 2-3 from the corresponding GAIM values.

In order to test the ability of our GAIM model to assimilate UV radiances and to test its impact on the electron density reconstruction, we also performed model runs of our GAIM model with and without assimilating the UV radiances. Figure 5 shows an example of one of these model runs. On the left side, the relative difference of the GAIM radiances and the LORASS 1356 Å radiances are shown versus tangent altitude when the UV data were not assimilated into GAIM. The right side of Figure 5 shows the same comparison, but this time after assimilating the UV radiances. The assimilation of the data slightly narrowed the distribution function and led to a more Gaussian distribution.



**Figure 5. Relative difference between the GAIM obtained radiances and the observed LORASS 1356 Å radiances versus tangent altitude. The left side shows the case without assimilating the data and the right side shows the results after assimilation of the UV radiances.**

Additional validation studies include the following:

- (1) Scherliess et al. [2006] validated the Gauss Markov Kalman filter model for three month-long periods in December 2001, January 2004, and March-April 2004. These validation periods covered different solar cycle, geomagnetic activity, and seasonal conditions. In addition, different amounts and different data types were assimilated. The results were compared to independent data sets. These independent data sets included NmF2 obtained from a dynasonde located at Bear Lake Observatory near Logan, Utah, and vertical total electron content observed by the TOPEX/Poseidon satellite over the oceans.
- (2) Thompspon et al. [2006] used the Gauss-Markov Kalman filter model to study the effect of slant TEC and electron density profile data on the model fidelity. In this study, the GMKF was run for several cases with varying combinations of slant TEC and EDP data during a 30-day study period. It was found that the assimilation of slant TEC from as many as 355 globally distributed

GPS ground stations significantly improved the comparison with independent data. Furthermore, the assimilation of only ionosonde data into GAIM improved the TEC comparisons over the globe, but introduced a bias in model NmF2 owing to the specifics of the EDP handling in this version of the GMKF.

- (3) Sojka et al. [2006] compared NmF2 values obtained from the GMKF with ionosonde observations over Australia during a 3-month long period.

#### *Collection of UV Observations from LORASS, SSULI, and SSUSI:*

We have worked with Pat Dandenault at NRL and Paul Strauss at AeroSpace Corporation on the collection of LORASS, SSULI and SSUSI observations. We have received month-long SSUSI UV radiances from Paul Strauss. This data was, however, not yet in the final operational data format, which is still under consideration. We have received week-long LORASS and SSULI 1356 radiances from Pat Dandenault, which were used in the above mentioned study by Scherliess et al. (2006).

#### *Collaborations about SSUSI and SSULI data format:*

We have worked with Pat Dandenault at NRL and Paul Strauss at Aerospace Corporation and Larry Paxton at APL on the definition of the UV data formats for the SSULI and SSUSI instruments.

### **IMPACT/APPLICATIONS**

The USU Gauss-Markov and Full Physics Kalman Filter models provide ionospheric specifications and forecasts on both global and regional grids. These specifications and forecasts are useful for DoD and civilian systems and operations, including HF communications and geo-locations, over-the-horizon (OTH) radars, surveillance, and navigation systems that use GPS signals.

### **TRANSITIONS**

Operational Version 2.2 of the Gauss-Markov model was delivered to the Naval Research Laboratory (NRL) and the Air Force Weather Agency (AFWA) on January 15, 2005, and Operational Version 2.3 was delivered to NRL, AFWA, and the Community Coordinated Modeling Center (CCMC) on July 15, 2005. The USU Full Physics Kalman Filter model is scheduled for delivery in 2008 and it will eventually be operational at both the Air Force Weather Agency (AFWA) and NOAA. Prior to this, the model will be used at NRL and the CCMC so that the output will be available to the scientific community.

### **RELATED PROJECTS**

This project resulted from a basic research MURI program called Global Assimilation of Ionospheric Measurements (GAIM). Research grade versions of our Gauss-Markov and Full Physics Kalman Filter models were developed under the MURI program, and this project provided funds to incorporate UV radiances into the GAIM models and to conduct scientific studies.

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